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Experimental Study on Temperature Measurement in Turning Operation of Hardened Steel (EN36)

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Abstract

In metal cutting, the temperature measurement of cutting tool is being influenced by cutting factors, especially in continuous cutting operation. Since the life of the cutting tool material strongly depends upon cutting temperature, it is important to predict heat generation in tool with reliable techniques. In this study, cutting tool's average temperature was investigated by placing analog K-type thermocouple sensor in cutting tool. CNMG4325 Grade TN2000 Coated carbide insert with shim has been taken as cutting tool and round bar of EN36 hardened steel as work piece. The Data acquisition has been done with bridging of Amplifier and LabVIEW software through Arduino UNO R3 controller board. According to the mathematical model and equations, generated by CCD based RSM, experiments were performed and cutting temperature was obtained. Results have been analyzed and optimization has been carried out for selecting cutting parameters.

Keywords: Thermocouple, turning, cutting temperature, coated carbide tool, Response Surface Method (RSM), Optimization, Arduino UNO

1. Introduction

In metal cutting industries, machining types, especially turning operation is very basic type of machining [1]. For certain processes in manufacturing, it is favorable and necessary to have certain knowledge about heat generation and temperature rise (including average and maximum temperature) during machining process [2, 3]. Increment in maximum temperature at clearance face or at rake face of cutting tool causes the reduction in life of tool. Similarly,

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quality of machined surface, a metallurgical structural alteration in tool and workpiece material also depends on the maximum temperature, temperature gradient and cooling rate of both tool and workpiece. Certain physical and chemical reactions that are developed during the cutting process are directly connected with tool wear, power consumption, surface roughness on work piece material and cutting temperature [4-6].

The natural low of thermal energy gives significant relationship between cutting temperature and cutting parameters in order to improvement of cutting tool's wok efficiency, quality and accuracy. The heat distribution in cutting tool, in formed chip and in workpiece material strongly depends on (mechanical and chemical) properties of cutting tool and workpiece material, cutting speed, depth of cut, feed rate, nose radius, geometry of tool, type of coolant used and other parameters [7-12].

Chu and Wallbank [13] in 1998 stated a relationship between the cutting parameters and cutting temperature for specific range of cutting speed and feed rate. Abdil and Yashya [13] has recently examined with comparative study of different to two cutting temperature measurement technique used simultaneously (i.e. Thermocouple and Infrared based technique) and concluded that the cutting speed was the parameter most affecting the tool-chip interface temperature whereas feed rate was not significant. While O'Sullivan and Cotterell [14] had done experiment on cutting tool's temperature while machining of aluminum AI 6082-T6 with help of k-type thermocouple and analyzed with LabVIEW but they have not used any methodology and taking just small amount of readings. It is noted that the force has been importance variable in the generation of surface temperature [14-17]. A FEM-experimental methods for obtaining the cutting tool's temperature fields developed and compared with physical conditions [13, 18]. Shihab [19] presented the RSM model based study using ANOVA for turning of AISI hard alloy steel.

This paper includes the study and experiment of appropriate temperature measurement techniques of cutting tool. This study also includes placement of thermocouple sensor, the data acquisition and the methodology for measuring cutting temperature and mathematical model to optimize the cutting conditions. Development of experimental setup also has been discussed over here with diagrams and figures.

1.1. History of Temperature measurement techniques in metal cutting process

Over the past century, mostly after successfully finding of heat generation concept by Count Rumford [20] in 1798 several temperature measurement techniques in cutting processes has been invented through history. Technique of temperature measurement includes: (1) thermocouple – artificial and natural thermocouple, (2) infra-red photography, (3) Optimal infrared pyrometer, (4) thermal paints, (5) Metallurgical change in work piece/cutting tool material, (6) Thermal Camera technique. Several detailed review is available in literature for these techniques of temperature measurement. Every method has its own pros and cons depending upon physically arrangements. Lowen and Shaw [21] developed an analytical prediction model for the measurement of cutting temperature. They came with conclusion that cutting temperature is a function of cutting speed and feed rate with following equation:

$$\theta_t = V^{0.5}\ f^{0.3} \tag{1}$$

where θ_t is the average cutting temperature, V is the cutting speed and f is feed rate.

In this study of temperature measurement, the most widely used K-type artificial thermocouple sensor was selected for the measuring of cutting tool's average temperature during turning operation. The values within certain range of cutting parameters like cutting speed, depth of cut and feed rate were selected and used for building the mathematical model using CCD based Response Surface Method (RSM). The temperature data of cutting tool was obtained by experimentation and the optimization of selected cutting parameters obtained successfully.

2. Data Acquisition

Temperature measurement device has to be versatile and flexible within a wide range of temperature values. So, Analog K-type thermocouple sensor were selected to measure the cutting temperature. Thermocouple works on the principle of Seebeck effect. Generally, thermocouple sensors are made by contacting two different metal material (here Chromel - Alumel) with welded tip and PTFE-insulated. The temperature produce by machining is in a form of voltage (in millivolt). K-type temperature sensors can measure temperature ranging from -200℃ to +1200℃.

3. Experimentation

3.1. Tool and Workpiece material

The workpiece material involve quenched and tempered EN 36 Hardened steel with improved machinability. This work piece material finds application in automobile and gear manufacturing. CNMG4325 Grade TN2000 tool insert with K20 shim were the material of tool used in experiment. As the work piece material is difficult to machine this carbide insert has been selected for experimentation. Table 1 represents the chemical composition of EN 36.

Table 1. Chemical Properties of EN36 Work Piece Material

Chemical	C	Si	Mn	P	S	Cr	Mo	Ni
Percentage (%)	0.153	0.229	0.490	0.012	0.012	0.788	0.126	3.020

3.2. Thermocouple sensor and Amplifier

For present study, standard K-type analog thermocouple were used for measuring the temperature of cutting tool in turning operation. Following table 2 gives the information of different characteristics of it.

Table 2. Technical specification of sensor

Parameters	Values
Needle length	150 mm
Sheath material	Inconel 600
Sheath diameter	2 mm
Temperature range	-200℃ to +1200℃
Positive Leg (wire)	Ni-Cr alloy (Yellow)
Negative Leg (wire)	Ni-Al alloy (Red)
Seebeck Coefficient at 100℃, $\mu V/℃$	41.4

As thermocouple sensor’s output is in analog and in microvolt, it is necessary to amplify the voltage for further processing. To do so, Analog K-type Thermocouple Amplifier (fig. 1) was used. This Amplifier has ability to amplify the input signal into sufficient voltage/current value from lower microvolt as its input. It take 3 to 36 VDC power supply and has higher input impedance as it has lower load. Since they are highly accurate with accuracy of 1 degree Celsius, it is most suitable for Thermocouple sensor. It will generate 5 mV per change in degree Celsius, i.e. temperature calculation is done as follows;

$$"Temperature\ (℃) = Vout(mV)/5mV \qquad (2)$$

3.3. Arduino UNO R3 board

After completion of amplification of Acquired signal, it is necessary to convert this amplified analog into digital form via some Analog-To-Digital convertor or using some data acquisition devices like Microcontroller, DAQ Cards, Arduino Boards, Application specific ICs, etc. For this work, Arduino UNO R3 board was selected as a Data Acquisition Device because of its compatibility with k-type analog thermocouple amplifier and simplicity in conception and programming. Fig. 2 shows the Arduino UNO R3 controller board.

Fig. 1. K-type analog Amplifier

Fig. 2. Arduino UNO R3 controller board

3.4. LabVIEW

LabVIEW is recent software for data acquisition method sensors and used by many industries. After the analog to digital conversion, the temperature measurements will be linearized by a cold junction compensator signal which is built into data acquisition hardware. LabVIEW (Laboratory Virtual Instrument Engineering Workbench), software developed by National Instruments (NI), is used to perform data collection and visualization of machining temperature. LabVIEW delivers extensive acquisition, analysis, and presentation capabilities in a single environment. The graphical temperature output developed in LabVIEW has been shown in fig. 3.

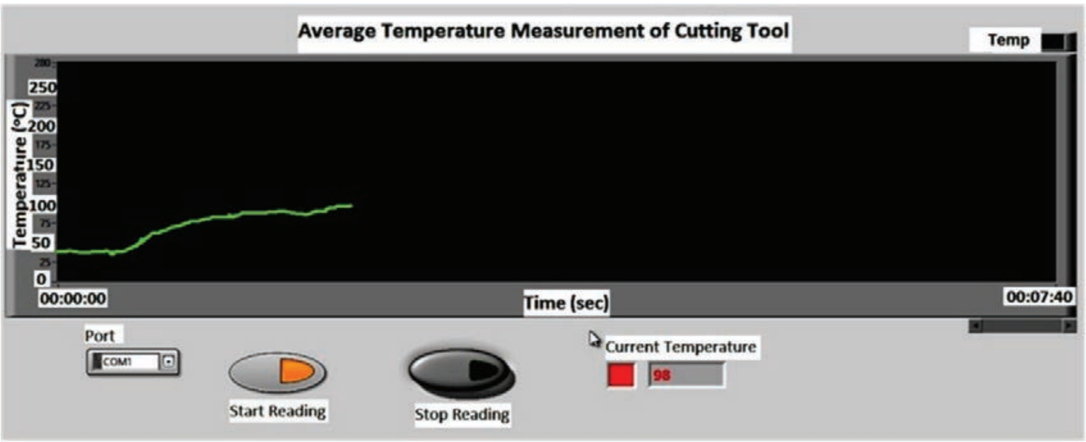

Fig. 3. Front Panel Screen of LabVIEW software

3.5. Placement of Thermocouple sensor in tool

For turning operation, specially formed K-type thermocouple sensor placed just right side of insert through hole made at right side of shim. In fig. 4 and fig. 5 position of the measuring point and method of thermocouple placement is presented.

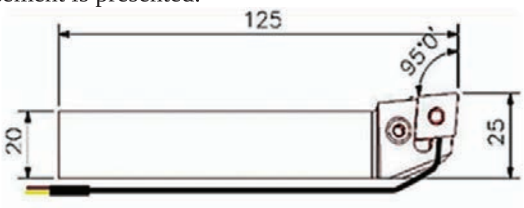

Fig. 4. Top view of placed sensor

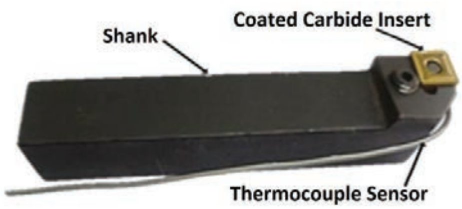

Fig. 5. Picture of tool with placed sensor

4. Experimental Procedure

4.1. Experimental setup

For understanding of set up, schematic diagram has been presented in fig. 6. In this setup, to measure cutting tool's average temperature, K-type thermocouple sensor were placed in cutting tool in such way that it can measure the average temperature of cutting tool. Since the thermocouple supplied calibrated, no need to calibrate it and didn't require cold junction compensate or any other junction that is far from hot junction to count the value. Using data acquisition of LabVIEW software, temperature data has been acquired, stored, and amplified.

Arduino UNO R3 board served as a communication bridge for sensor and computer according to the installed program in IC (Atmel358P). It contains analog and digital channels like analog input, analog output, digital input and digital output. Among those input and output pin family, Analog Input pin A0 has been used as an input from thermocouple sensor via amplifier. Amplifier needs +5V Power supply which is available in Arduino Board as in-built function. Through Serial cable, signal was transferred to the LabVIEW software in computer.

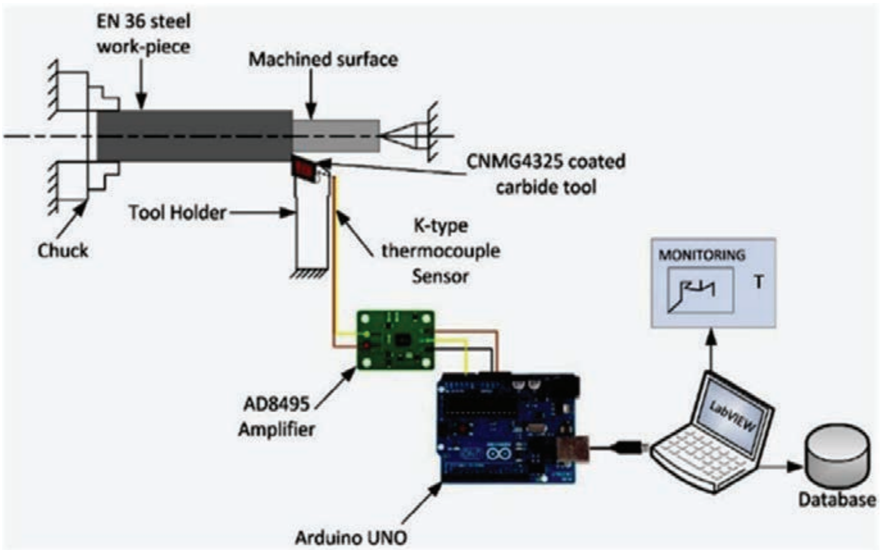

Fig. 6. Illustration of Experimental setup

4.2. Experimental conditions

The Central Composite Design (CCD) based RSM was used for the determination of optimum control factors 3-level factor design with center point six was selected. Values of those factors had been achieved with consideration of the machine tool capacity. There were total 20 combinations of the turning runs were carried out using design expert software to complete experimentation. The experimental conditions with values of level for cutting parameters are shown in below table 3.

Table 3. Cutting conditions with its levels

Parameters	Level 1 (-1)	Level 2 (0)	Level 3 (+1)
Cutting Speed (rpm)	450	710	1120
Depth of Cut (mm)	0.40	0.80	1.20
Feed Rate (mm/rev)	0.180	0.355	0.560

5. Analysis of Results

Central Composite Design based Response Surface Methodology was selected in this work [22]. RSM require more data compare to the Taguchi method to ensure the optimum condition [23, 24]. RSM relates the independent input variables with output (process response). Design Expert software was used and obtain the set of experimental runs of CCD which would help to investigate the influence of three cutting parameters (cutting speed, depth of cut and feed rate) on the output (cutting temperature). Table 4 shows the CCD with its output as a temperature.

Again this data had been utilized to analyze through Design-Expert Software. The result of Analysis of Variance (ANOVA) has been carried out and as per Table 5 the value of R-squared (0.9371) and predicted R-squared (0.9028) were obtained.

Table 4. Experimental results with run

Run	A: Cutting Speed [rpm]	B: Depth of Cut [mm]	C: Feed Rate [mm/rev]	T: Temperature [℃]
1	450	0.40	0.180	95
2	710	0.80	0.355	108
3	1120	1.20	0.180	135
4	710	0.80	0.355	108
5	1120	0.40	0.560	110
6	450	1.20	0.560	150
7	450	1.20	0.180	125
8	1120	1.20	0.560	130
9	1120	0.40	0.180	115
10	710	0.80	0.355	108
11	450	0.40	0.560	117
12	710	0.80	0.355	108
13	710	0.80	0.180	100
14	710	0.40	0.355	85
15	1120	0.80	0.355	126
16	710	0.80	0.355	108
17	450	0.80	0.355	115
18	710	1.20	0.355	135
19	710	0.80	0.560	114
20	710	0.80	0.355	108

Table 5. Value of R-Squared and Adjusted R-squared

Std. Dev.	4.87	R-Squared	0.9371
Mean	115.00	Adj R-Squared	0.9028
C.V. %	4.23	Pred R-Squared	0.7300
PRESS	1119.10	Adeq Precision	18.691

From this ANOVA result there was also relationship obtained in form of equation as shown in equation 3 which relates the input and output parameters after backward elimination insignificant model terms from it.

Following is the final equation in terms of Coded Factors:

$$T = 108.04 + 1.70 * A + 15.15 * B + 4.52 * C - 3.38 * A * B - 6.83 * A * C + 13.49 * A^2 \qquad (3)$$

Fig. 7 implies the effect of cutting temperature on individual cutting parameters. The change in Depth of cut has very high effect on cutting temperature while cutting speed and feed rate have moderate effect on cutting temperature. For the given range of cutting parameters, feed rate has been found as the most significant parameter.

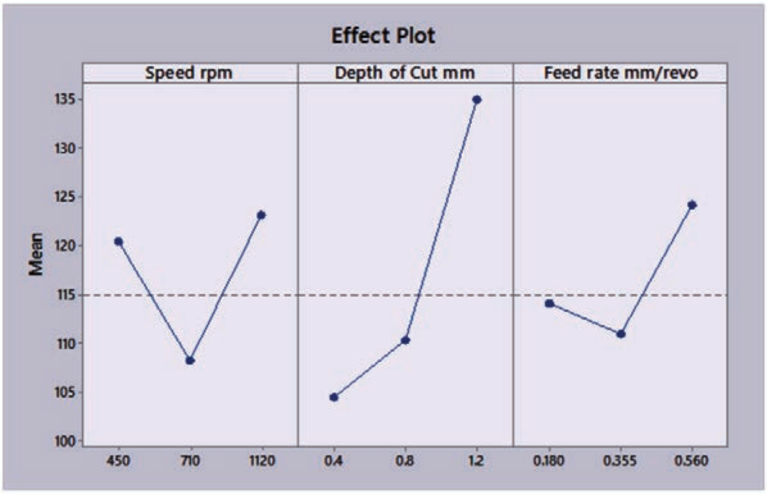

Fig. 7. Main Effect Plot of Cutting Temperature

6. Condition Test

To ensure that the results has same effect over the range of each affecting factor in experiments, additional experiments have been carried out taking values of different factors between its starting and ending limits. According to the empirical equation temperature output has been predicted and the values of it are presented in table 6. The error percentage is within permissible limits and therefore empirical equation based on RSM can be utilize to predict the cutting temperature values for any combinations of three cutting parameters within the range of experiments performed.

Table 6. Condition test with results

Run Order	Cutting Speed [rpm]	Depth of Cut [mm]	Feed Rate [mm/rev]	Temperature [°C] (Predicted)	Temperature [°C] (Measured)	Error (%)
1	710	0.60	0.20	95	103	8.40
2	450	0.90	0.315	122	116	4.91
3	1120	1.10	0.450	131	132	7.63

7. Optimization

In this study, RSM has been utilized for single response optimization. The use of response surface optimization helps to calculate the optimal values of input in order to minimize the cutting temperature during the hard turning process of EN36 steel. The constraints for optimization of cutting parameters have been shown in table 7. Table 8 shows the values for the input parameters for minimizing temperature. It is clearly seen that obtained optimal value is 85.7407 ℃ for the respective values of cutting speed, depth of cut and feed rate.

Table 7. Constraints for Optimization of parameters

Parameters	Lower limit	Higher limit
Cutting Speed (rpm)	450	1120
Depth of Cut (mm)	0.20	1.20
Feed Rate (mm/rev)	0.180	0.560

Table 8. Optimization Results

Cutting Speed	Depth of Cut	Feed Rate	Temperature	Desirability
637	0.40	0.180	85.7407	0.989

8. Conclusion

This paper focused on single k-type thermocouple sensor for measuring the average cutting tool temperature during turning operation on lathe machine with work piece material as EN series grade 36 steel round bar and coated carbide as cutting tool. This paper included the effect of cutting temperature on different parameters like cutting speed, feed rate and depth of cut. Based on the results following conclusions can be made:

- Mathematical empirical model of temperature measurement has been developed for EN36 as work piece material and coated carbide insert as tool material.
- Mathematical model has been validated by experimental tests and the error in temperature measurement found to be less than 10%.
- Optimized values of cutting parameters have been achieved for minimum temperature with desirability of 98.9 %, which is highly acceptable.

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